Heterodyne Radiometer Development for the *Earth Observing System Microwave Limb Sounder*

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ABSTRACT

The gradual depiction of the Earth's stratospheric ozone and the regular appearance of deep ozone 'holes' over the polar regions has dramatic ramifications for our planet. NASA'S Mission to Planet Earth is attempting to address this and other issues related to environmental change through extensive scientific investigation and global monitoring. As part of this effort, the Earth Observing System Microwave 1 imb Sounder (EOS-MLS), Joe W. Waters, Principal Investigator, was proposed and is currently in development. This instrument will use heterodyne radiometers in the millimeter and submillimeter wavelength region of the electromagnetic spectrum to globally map radicals, reservoirs and source gases in all of the four major ozone depleting chemical cycles as well as volcanic pollutants and stratospheric and upper tropospheric water.

The Submillimeter-Wave Radiometer Development group at JPL along with collaborators at the Rutherford Appleton Laboratory in the United Kingdom and a small number of US laboratories are developing space-borne radiometer components to satisfy the detection requirements for EOS-MLS from 200 to 650 GHz with possible extension up to 2.5 THz (1 19 pm). This conference paper summarizes the development that has been ongoing, with emphasis on the millimeter- and submillimeter-wave mixers. Detailed design and performance data for a subharmonically-pumped antiparallel-pair planar-diode mixer arc presented including computational simulations and measured mixer noise and conversion loss at ?.15 and 640 GHz. Results from a modest test program comparing the performance at215 GHz of planar GaAs antiparallel-pair mixer diodes, planar $In_{53}Ga_{47}As$ devices, GaAs planar-doped-barrier diodes and a GaAs millimeter-wave integrated circuit (MMIC) mixer arc also presented. Finally, current and future development efforts in the areas of submillimeter-wave local oscillators, integrated planar-diode mixers, IF amplifiers and THz radiometers arc outlined.

I. INTRODUCTION

The submillimeter wavelength spectral band, covering the frequency range 300 GHz (1 mm) to 3 THz (0.1 mm), represents one of the least explored yet information rich segments of the electromagnetic spectrum. This frequency span encompasses all of the critical spectral emissions from the key molecules involved in atmospheric chemistry both on Earth and on the planets. These include those molecular transitions which have been identified as crucial to our understanding and monitoring of the global ozone depletion problem. The submillimeter-wave regime also contains spectral line emissions which can further our understanding of interstellar chemistry, new star formation and galactic structure. Due to high atmospheric opacity both astrochemical and stratospheric observations in the submillimeter-wave spectral bands must be made from high altitude aircraft, balloons or satellites. There are currently two funded NASA space missions which will carry submillimeter-wave radiometers; Submillimeter-Wave Astronomy Satellite (SWAS) and Earth Observing System Microwave Limb Sounder (EOS-MLS) and two missions which have been or are in pre-phase A study; Submillimeter Intermediate Mission (SMIM) and Large Deployable Reflector (LDR). SWAS has two radiometers at frequencies of 490 and 547 GHz and EOS-MLS is currently configured with radiometers at ?.15, 440 and 640 GHz and potential channels at 1.2 and 2.5 THz (Table I). SMIM and LDR are designed to have broad spectral coverage beginning at 400 GHz and going up to or beyond 1100 GHz.

All of these missions require the high sensitivity and narrow spectral response available with heterodyne radiometers, Such radiometers generally consist of a low loss signal coupling structure (waveguide feed horn or small antenna), a local source of RF power (local oscillator, LO) at a frequency very close to that of the observed signal, a frequency diplexer for combining the signal and LO, a low noise frequency downconverting element (Schottky barrier diode or superconducting tunnel junction), a mount or housing which efficiently couples the RF signal and LO into the downconverting element and takes the beat or intermediate frequency (IF) out, a low noise amplifier, usually in the microwave band, to boost the IF by ~60dB without significantly degrading the signal-to-noise ratio, and finally a high resolution filter bank to separate out the individual spectral lines.

In the push to obtain ever higher sensitivity, shorter observation times and the use of smaller collecting surfaces, the submillimeter-wave astrophysics community has devoted much of their re.sources towards the development of radiometer front ends based on the refractory superconductors niobium and niobium nitride. At present the most prevalent form of high frequency superconducting heterodyne receiver is the small area superconductor-insulator-superconductor (SIS) tunnel junction which offers the potential of near quantum limited sensitivity throughout the millimeter-wave bands and possibly at frequencies as high as 1.4 THz. However, the requirement for a liquid helium ambient environment poses a significant limitation for remote, long-lifetime space operation, Nevertheless, significant progress is being made on both junction reliability and cryocooler technology and there seems no doubt that SIS receivers will fly in space sometime in the very near future.

For most observations in the Earth's atmosphere sensitivity is not nearly as critical an issue as it is for stellar astrophysics. A large number of key molecular transitions can be observed with the sensitivity available from current room-temperature or passively cooled semiconductor-diode radiometers. For the most part, the emphasis for millimeter and submillimeter-wave Earth remote sensing applications has been on pushing to higher frequencies, increasing the instantaneous bandwidth, improving device reliability and reducing radiometer complexity and cost.

For more than two decades the best uncooled heterodyne radiometers for use in the 100-600 GHz frequency range have been composed of waveguide mixers with whisker-contacted metal-semiconductor Schottky-barrier honeycomb diodes and solid-state oscillators followed by whisker-contacted semiconductor varactor-diode frequency multipliers to generate the required local oscillator power.

Both of these critical receiver components currently use a very small (≈75 μm cubed) GaAs diode chip held in place on a filter structure and contacted by a thin (6-12 μm diameter) pointed wire (whisker) stretched across a narrow waveguide channel. For space applications, each device must be assembled under rigorous quality control standards, an extraordinarily time consuming task. In addition there is a considerable variation in performance from laboratory to laboratory, even at 100 GHz, due to subtle design differences, mechanical tolerances and uncontrolled parameters in the diode fabrication process. The entire mechanical structure reaches a practical limit around 600 GHz where the waveguide size becomes comparable to that of the diode chip itself.

In order to reduce the assembly cost and improve the reliability and reproducibility of heterodyne receivers for our present and planned space missions throughout the millimeter and submillimeter wavelength bands two major changes must be incorporated into current radiometer design. First, the whisker-contacted honeycomb diode must be replaced by a more reliable, easier to handle, integrated structure similar to the beam-lead diodes now routinely used below 100 GHz. Second, for applications at or above 600 GHz, the diode must be integrated with the remaining, physically larger, mixer circuitry to increase flexibility and simplify assembly. An added benefit to this latter approach is the potential of going one step further and replacing the last remaining mechanically fabricated component, the waveguide mount, with an all planar photolithographic structure scalable to frequencies well beyond a 1 THz.

A major goal of our radiometer development effort under EOS-MLS is to advance the state-of-the-art in n~illirnctcr-wave planar-diode technology to the point at which it can be used readily at frequencies as high as 2.5 THz. Under the scope of this effort wc arc working on improved planarization techniques for both mixers and frequency multipliers, integrating diodes with RF and IF circuitry, reducing device and circuit parasitic and exploring new semiconductor-diode material systems. Since both time and resources arc limited, and major technical leaps generally are not looked upon favorably within the constraints of the NASA space applications programs, we have been attempting to build upon existing technology rather than relying on new inventions. h-r this way wc hope to be able to remove the radiometer front end from the critical development path so that more resources can be devoted to increasing the science yield from a given mission.

The purpose of this conference paper is to summarize our results to date, focussing specifically on the first receiver channel to be developed (at 215 GHz), and to indicate the directions of our future efforts. Section II describes our scalable (?00-640 GHz) planar-diode mixer mount. Section III presents the results of a planar-diode test program to compare the performance (at 215 GHz) of discrete devices of varying geometry, substrate configuration and material construction. Section IV contains the results of some computed mixer performance simulations which indicate the potential benefits and pitfalls associated with our current diode configurations. Some preliminary measured and computed performance data at 640 GHz are given in Section V. Finally, in Section VI, progress and plans in related areas of EOS-MLS front-end radiometer development arc outlined.

II. PLANAR-DIODE WAVEGUIDE-MIXERS FOR 215, 440 & 640 GHz

Duc in large measure to the efforts of the authors of [1 -3], high-quality low-capacitance planar-integrated GaAs Schottky-barrier diodes arc now available for millimeter wavelength applications. They have already found their way into at least one space-borne platform, Advanced Microwave Sounding Unit (AMSU-B), a British Meteorological Office instrument with a water-vapor radiometer centered near 183 GHz and built by Aerojet Electronic Systems [4]. Using only slight modifications to existing wllisker-corltaclccl-diode waveguide-mixer designs, it is possible to substitute the planar diodes, forming fundamental, balanced or harmonic mixer configurations. [n addition many whisker-contacted-diode mixer designs which were considered previously to be mechanically impractical, can now be implemented using the planar diodes. One of these configurations, the subharmonically-pumped antiparallel-pair diode arrangement (SHP mixer), is particularly attractive for space borne applications. 7 he SHP mixer configuration was described by [5-6], accurately analyzed by [7] and very successfully demonstrated at millimeter wavelengths using whisker-contacted diodes by [8-9]. Benefits include subharmonic pumping (1.0 at one-half the observed signal frequency), simple RF diplexing and inherent local oscillator noise suppression [6,1 O], all very useful for submillimeter-wave operation. -lwo disadvantages of the antiparallel-diode pair configuration arc: an increased LO power requirement, especially in the case of unbiased diodes and, at least for the whisker-contacted configuration, a mechanical structure which is much more difficult to implement. As pointed out in [7] there arc also constraints on the obtainable mixer performance due to the practical realization of the diode circuitry (e.g. loop inductance between the diode pair).

Since the SHP mixer concept was first demonstrated at millimeter wavelengths by the Radio Astronomy group at Bell Laboratories [8-9] several groups [11 -15] have reported on similar mixer configurations but without realizing the performance obtained by the original investigators [Table II]. 1 his is perhaps due in part to the difficult mechanical configuration and, as wc show in Section III, to the difficulty of matching the waveguide circuit to the diodes. Never-the-less, since the performance of the subharmonically-pumped antiparallel-pair-diode mixer had been demonstrated to match that of the best single-diode fundamental mixers, at least at 115 GHz [8], wc decided to prototype a SHP waveguide-mixer mount which could be scaled to 640 GHz and which would be designed specifically to accommodate planar antiparallel-pair diodes.

Several guidelines were imposed on the design to help ruggedize, as well as simplify, construction and assembly. These included: using a single quartz microstrip line to hold the diodes and separate the signal, LO and IF ports, a minimum cross sectional dimension of 50X100 μm for the quartz at 640 GHz, simple solder or wire bond contacts for all elements, relatively straightforward machining requirements for the waveguide Mocks and, at least initially, broad RF tuning capability to take advantage of variations in available diode characteristics. Both computer simulations and microwave scale modelling were used to fine tune the mount characteristics and to determine optimum input and output impedances, sideband response and accessible tuning locus, parameters not easily measured at millimeter wavelengths. For operation at 215 GHz, it was possible to use discrete planar diodes separately mounted cm the quartz micros! rip line. For 640 GHz, a technique for integrating the diodes with the quartz microstrip circuitry was developed. The resulting mixer design appears in Fig. 1 and is described fully in [16].

III. PLANAR-DIODE PERFORMANCE COMPARISON AT 215 GHz

Coupling the mixer block of Fig. 1 with discrete planar antiparallel-pair GaAs Schottky diodes of the type described in [15] wc have been able to better slightly the Bell Laboratories' whisker-contacted SHP-mixer performance at 200 GHz [1'able Ii]. Since our results were first reported [1 6], wc have been evaluating other prepackaged planar diodes of varying construction and electrical properties in an effort both to improve upon the current mixer noise performance and to reduce the required LO power. Planar diodes in antiparallel-pair packages of the type described in [15] and made at the University of Virginia and at JPL, $In_{53}Ga_{47}As$ diodes of similar construction made at the University of Virginia [1 '/], GaAs planar-doped-barrier devices made at the University of Michigan [18], GaAs MMIC devices fabricated at Martin Marietta Laboratories [19] and a GaAs MMIC mixer with separately biased diodes [19] have all been tested between 2.00 and 230 G}Iz. Individual diode characteristics and the best performance data from each device category are displayed in Tables III and IV.

1 he best SHP mixer performance to date has been obtained with the University of Virginia small-package GaAs devices, type SC1T4. The nominal anode diameter for these devices is 1 μm and therefore they have very low zero bias capacitance ($\approx$3 fF). Diode pair uniformity generally is excellent and it is not necessary to use offset biasing to balance the current flow in the two devices during measurements. An attempt was made to determine the effect of the anode finger length on the mixer pcrformancc, but variations in diode characteristics and mount tolerances so far have masked any differences which might have shown up using finger lengths from 10 to 50 pm. Computer simulations (see section IV) indicate that much better performance may be obtained by optimizing the anode finger length and diode pad-to-pad capacitance. This possibility is currently being explored. It should also be mentioned that the inherent LO noise suppression available from the UVa diodes was measured and found to vary from 33 to 36 dB over an IF band of 1,2-1.8 GHz. This allowed us to usc a very noisy, but widely tunable, backward-wave oscillator for our 1.0. The sideband ratio was also measured, and for an IF' of 1.5 GHz, was generally found to be better than 0.5 dB at the optimal tuning position.

Diodes made by the same process as the UVa SC1T4 devices, but using JPL grown epitaxial material (type KD138), consistently gave somewhat poorer mixer performance despite similar DC current-voltage and IF noise characteristics. Differences in performance may be clue to anode diameter, wafer doping profile variations (the JPL material has somewhat higher background doping levels in the insulating buffer layer and a thinner n+layer), differing capacitance-voltage curves (these have not been accurately measured) or a combination of other small variations in electrical characteristics. Additional performance comparisons will be made in the future.

In order to reduce circuit parasitic, especially pad-to-pad capacitance, wc wanted to measure the discrete packaged diodes without the high dielectric constant GaAs Substrate present. A substrate etching and replacement technique developed at the University of Virginia [3] has been used to produce nigh quality planar antiparallel-pair diodes with a 5 μm GaAs layer glued to a much thicker (100 μm) quartz substrate [diode type SR2T1]. 7 he GaAs-on-quartz devices which we measured are similar in electrical characteristics to the SC1T4 diodes but have somewhat larger substrate areas and longer anode fingers. A limited number of samples were tested and the mixer performance proved to be very similar to that obtained with the SC1T4 all-GaAs diodes with a general reduction in required LO power. The larger substrate area, the presence of tile optical adhesive (between the GaAs and quartz) and the longer anode finger lengths make it difficult to form a positive conclusion concerning the benefits of the quartz package at this time. In an additional step, the quartz was removed on one diode sample leaving only a 5 μm thick GaAs device on the mixer filter circuit [diode SR2T1/G5]. This step caused a slight degradation in performance in our mixer block but further improved the LO coupling efficiency. Since wc were unsuccessful at removing the quartz from a pretested device we can not say for certain that the observed performance degradation was duc exclusively to the change in substrate, however it has been suggested [20] that excessive diode heating (and hence poorer performance) could result from the reduced thermal conductivity of the thinned substrateless GaAs device. More data will have to be accumulated before this conclusion can be verified.

For the 440 and 640 GHz radiometer channels on EOS-MLS, the local oscillator must be supplied by a frequency multiplied GUNN diode which, at the current time, limits the available power to only a few milliwatts. It is possible to reduce the LO power requirements for an antiparallel-diode pair by allowing each diode to be biased separately, at the expense of added circuit complexity, or by reducing the Schottky barrier height (turn on voltage knee) of the two devices. For the latter approach, $In_xGa_{1-x}As$ offers significant potential. Varying the iridium concentration from a high of 53% to zero results in a Schottky barrier height range of $\approx$.3 to 1 V, InGaAs also has a higher electron mobility (potentially lower series resistance) and a lower ohmic contact resistance (allowing smaller ohmic pad area), The disadvantage of using InGaAs is the poor lattice match to typical semiconductor wafer materials making defect free MBE growth difficult. When iridium phosphide is used as a substrate good quality $In_{53}Ga_{47}As$ epitaxial material can be grown and the resulting diodes have reasonably good DC characteristics. In a process developed at the University of Virginia [17], $In_{53}Ga_{47}As$ antiparallel pair diodes were produced on iridium phosphide substrates and were tested in the 200 GHz mixer blocks. As expected, the required LO power was substantially less using the $In_{53}Ga_{47}As$ diodes (below 1 mW in some cases). The noise performance of the diodes with the indium phosphide substrate [FLi2/A5] was mediocre, but when the iridium phosphide substrate was removed with a differential etch the performance improved by almost 3 dB [FLi2/A4]. Similar mixer noise temperature was obtained with the thinned $In_{53}Ga_{47}As$ device glued to a quartz substrate [FLi1/A1]. Even with the thinned devices the performance of the $In_{53}Ga_{47}As$ diodes is about 3 dB worse than GaAs devices of the same geometry. This is likely due to the much higher saturation current (10^{-6} compared to 10-'6) 01 the $In_{53}Ga_{47}As$ diodes. Numeric simulations, such as those described in the next section, confirm that there is a direct trade-off between diode saturation current and mixer conversion loss.

Planar-doped-barrier diodes [21] have an advantage over antiparallel-pair devices in that the two diodes are aligned vertically in the substrate thereby requiring only a single anode finger for DC contact (no loop inductance). The barrier height can be altered, as in $In_xGa_{1-x}As$ devices, by varying the device structure. Barrier heights from .3 to .7 V have been fabricated at the University of Michigan [18]. The disadvantages of the planar-doped-barrier diodes are higher diode ideality factor (>2 in practice), higher parasitic resistance (> 10 Ω) and, as with the $In_xGa_{1-x}As$ diodes, in the inverse relationship of leakage current to barrier height. GaAs planar doped barrier diodes made at the University of Michigan in a variety of package sizes and contact finger lengths were measured in the 200 GHz mixer blocks. The best performance has so far been obtained with the device whose characteristics are given in Table III [UMPDB-3]. Conversion losses at least 3 dB higher than GaAs Schottky diodes are expected duc to the high ideality factor (2.2) and the high series resistance ($\approx$20 Ω). The required LO power however is very much reduced (<1 mW) over that of the GaAs Schottky diodes duc to the lower barrier height. In fact, the LO power required for the planar doped barrier devices is slightly less than that needed for the $In_{53}Ga_{47}As$ diodes, which have a lower barrier height (turn on voltage around .1 V compared to .2 V for the planar doped barriers). This implies that the RF match, at the LO frequency, to the GaAs planar doped barrier devices is much better than that of the $In_{53}Ga_{47}As$ diodes. Additional batches of planar doped barrier diodes have been fabricated with lower series resistance and lower saturation current and will be evaluated in the coming months.

A second approach to lowering the required LO power for the SHP mixers is to separately bias the two back-to-back diodes. This can be readily accommodated in a GaAs MMIC circuit which has the added advantage of combining all r-nixcr filter circuitry and power coupling components on an easy to handle wafer. LO and IF components might also be integrated in, allowing a complete heterodyne front end to be fabricated on a single chip. MMIC mixer circuitry is now fairly common below 100 GHz but, until recently, it has not been extended into the short millimeter wavelength bands. As part of a program to develop GaAs MMIC circuitry for frequencies at 200 GHz and beyond, Martin Marietta laboratories designed and fabricated a complete GaAs MMIC mixer chip using the St IP antiparallel-pair diode configuration [19]. 7 he planar diodes arc fabricated using MMIC compatible mesa and airbridge techniques to isolate the devices and form the required circuit links. Anodes are formed using evaporated titanium-platinum-gold contacts and have a lower barrier height than the UVa electroplated platinum-gold devices (.9 rather than 1.1V). The mesa diodes also have very short anode finger lengths ($\approx 12 \mu m$). To compare the performance of the MMIC diodes with the other devices we have measured at 200 GHz, a pair of diodes [MM2-I3/B4] was diced from the MMIC wafer and mounted in the JPL St IP mixer blocks. 7 he noise performance is shown in Table IV and it is somewhat higher than might be expected from the DC diode characteristics. We believe most of the excess conversion loss and the higher than average required LO power can be attributed to the two-times-greater diode anode diameter (2 instead of 1 pm), since similar performance degradation was observed with UVa style diodes of the same area. Additional loss may also be duc to the larger GaAs substrate and higher diode saturation current. When the complete MMIC chips were tested in separate waveguide blocks [19], the mixer performance was somewhat worse as can be seen in the last line of Table IV. 'I he separate diode biasing arrangement however allowed us to reduce the required LO power to respectable levels (<3 row). Further work on the MMIC structure is ongoing,

Finally, as the first step towards integrating the UVa planar antiparallel-pair diodes with our existing quartz microstrip filter circuitry we have developed a process for fabricating wafer-scale GaAs-on-quartz hybrid substrates, where the GaAs diodes become an integral part of the quartz filter. 1 est structures are currently being fabricated for 215, 440 and 640 GHz operation and results will be reported upon soon,

To summarize, the best results with planar antiparallel-pair diodes to date have been obtained with the UVa type SC1T4 1μm diameter devices. 7 he performance of SHP mixers containing these devices is better than that of the best whisker contacted mixers at the same frequency. Improvements in the diode electrical characteristics such as lower ideality factor and reduced pad-to-pad capacitance as well as better circuit design theoretically could improve the mixer sensitivity by at least 2-3 dB [see section IV]. $In_xGa_{1-x}As$ devices show some promise for reduced, LO power consumption without undue increase in mixer noise but there is a definite trade-off between saturation current and barrier height that may limit the realizable gains. 7 his trade-off shows up in both the measured and computed performance, Planar doped barrier diodes also offer reduced LO power at the expense of noise temperature and, due to their added circuit simplicity (single anode finger) may provide easier RF matching. MMIC mixers offer the most promise for low cost, high reliability millimeter-wave receivers but further circuit work is indicated. A compromise between a complete GaAs MMIC mixer and a discrete diode package may be achievable using GaAs-on-quartz substrate forming techniques, but these hybrid devices have not yet obtained the performance level required for EOS-MLS.

IV. COMPUTED MIXER PERFORMANCE AT 215 GHz

Conversion loss and impedance measurements made on an X-band scale model of the millimeter-wave mixer allowed us to determine a set of desired embedding impedances for the 200 GHz planar diodes (exclusive of pad-to-pad capacitance and diode loop inductance). These impedances were then used in a nonlinear mixer analysis program [7,22] along with the planar-diode current-voltage (IV) and capacitance-voltage (CV) characteristics to compute the performance of the subharmonically pumped mixer. For the simulations which are presented here, the fundamental and second harmonic mount embedding impedances at the tuning position which gave the lowest mixer conversion loss on the scale model were used in the mixer analysis program. Higher harmonics were short circuited outside the diode. 7 he diode pair was assumed to have an IV relationship which follows the standard thermionic emission equations and parameter values R_s, I_s, η and ϕ, were obtained from the measured DC IV curve. 'I'he CV relationship is derived from Poisson's equation and has the usual inverse square root dependence for a uniform doping profile. As in [7], the diode loop inductance is plotted as a variable for a given embedding impedance set and frequency. As a second variable, a parallel capacitance has been added across the diode pair to represent pad-to-pad capacitance. Doth of these parasitic elements were not accounted for in the scale model measurements.

The results of two sets of simulations, using diode characteristics typical of the UVa SC1T4 devices with 1 and 2 μm diameter anodes, arc shown in Figs. 2 and 3. The computed single sideband mixer noise and conversion loss are shown as a function of diode loop inductance (anode finger length) and pad-to-pad capacitance. It is not clear where the diodes in Table III fall along the curves in Figs. 2 and 3 as wc have not yet derived an accurate equivalent circuit model for these devices, I-he diode pad-to-pad capacitance can be measured indirectly using wafer probing techniques or by scale modelling and values for the diodes in 1 able III fall somewhere between 3 and 6 fF depending on anode finger length and substrate dielectric constant.

Looking at Figs. 2 and 3, it is interesting to compare the measured and computed performance of the 215 GHz mixers. I'here is qualitative agreement over a reasonable set of parasitic parameter space, but closer matching has not yet been possible. Clearly the variation of computed mixer performance with diode parasitic parameters is considerable. Much better mixer performance than has been obtained seems possible for the subharmonic pair configuration if the diode anode size, the pad-to-pad capacitance and the anode finger length are optimized in unison. Single ended fundamental mixers do not seem to have as much variation in performance with these parasitic and therefore may be much more forgiving when designed without optimization of specific junction parameters.

V. MEASURED AND COMPUTED PERFORMANCE AI" 640 GHz

The 440 and 640 GHz mixers for EOS-MLS require an added level of integration to avoid an overly small diode package size. The hybrid GaAs-on-quartz arrangement described briefly in section III can meet the requirements assuming there is no loss in receiver sensitivity duc to the mechanical configuration or constraints on the diode electrical performance. The 215 GHz StHP mixer block was readily scaled to 640 GHz with the only differences being in the attachment of the signal feed horn (a standard waveguide flange was not used) and in the relative dimensional tolerances (unfortunately, much higher at 640 GHz.). Our original intent was to test this mount with the integrated GaAs-on-quartz devices but diode processing problems have delayed this. In the meantime, wc measured the 640 GHz mixers with available discrete diode pairs of 1 and 2 μm nominal anode diameter. 7'0 fit the diodes in the signal waveguide they were soldered in position on the 50X100x?.500pm quartz filter and then individually thinned to less than 20μm using a mechanical lapping process (chemical etching was not possible with the available devices). A315 GHz carcinotron was used to generate LO, as coupling to the diodes was extremely poor (> 1 7 mW was required). The best performance so far obtained is a single sideband mixer noise temperature of 18,000 K, and a conversion loss of 15 dB. [n order to determine how much of the conversion loss was due to RF mismatch and how much to the diode parasitic, we ran some computer simulations of the expected mixer performance using actual diode IV data, optimized RF embedding impedances and varying pad-to-pad capacitance as a function of diode loop inductance. The curves for diodes with both 1 and 2 μm diameter anodes appear in Figs. 4 and 5. The computed performance agrees qualitatively with the measurements for reasonable choices of inductance! and pad-to-pad capacitance, Only thermal and shot noise sources were considered in the analysis and no RF losses were assumed. The simulation predicts 11-20. mW of required 1..0 power for the 2μm diameter diodes and 5-11 mW for the 1μm diodes. The diodes which gave 18000K SSB were type KD138 [see I'able III] and have a nominal diameter of ≈1.4 pm. The results indicate that smaller anodes are needed as well as lower parasitic pad-to-pad capacitance. Direct write E-beam diodes are now being fabricated with the hybrid integrated filter process and will be tested soon.

Vf. ADDITIONAL RADIOMETER DEVELOPMENT EFFORTS

[n addition to the development of planar-diode waveguide mixers wc have been or arc planning to begin working on several other components: integrated HEMT amplifiers to satisfy the broad IF bandwidth requirements, planar-diode multipliers to satisfy the LO requirements at 440 and 640 GHz, a 2.57 Hz planar-diode fundamental mixer for 0} I and a 2.5 THz laser local oscillator source.

1-20 GHz MMIC HEMT amplifiers with high input impedance (> 100 Ω) for directly matching to the output port of the StHP mixers have been designed and fabricated by Martin Marietta laboratories and arc currently being tested. Significant progress has also been made on a high input-power-handling planar-series-arrayed varactor-diode multiplier for 160 GHz by the group at the University of Virginia in collaboration with Dr. Neal Erickson at the University of Massachusetts. Results on [his work will appear in publication shortly. Several commercial companies have expressed interest in the 2..5 THz laser local oscillator and system design work should begin in this area by late Spring.

VU. SLIMMARY

In its current configuration, EOS-MLS requires an ambitious development program which can only bolster the already growing effort in the microwave community to push heterodyne receiver technology well into the THz frequency range, It contains both exciting technology development and challenging engineering. Besides our principle thrust, to replace the whisker-contacted diode with a planar-integratable structure, EOS-MLS has provided justification for several development efforts not directly sponsored by the project and some which are only very remotely related! Due to its long term status under the Mission to Planet Earth program and its importance in furthering our understanding of ozone depletion chemistry, EOS-MLS brings a great deal of legitimacy to our technology development efforts in the subn~illin?ctcr-wavelength bands. The spin-offs from this program should find applications in other areas as well, and we hope the push towards higher frequencies, higher sensitivity and higher reliability continues to spur development in this very challenging area.

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Table 1. Focussed EOS-MLS Spectral Bands and Measurements

Radiometer Center Freq.	I.F. Band Center	Primary Measurement	Secondary Measurement	Required Sensitivity 0.6" integ., SSB
216.29	10.15	" 0, (UARS) "		T_{sys} < 3000 K
	11.95	upper troposphere H_2O	ClO (UARS)	
	17.65	pressure/temperature		
	20.90	upper troposphere O_3		
442.99	3.75	lower stratosphere H_2O, O_3		T_{sys} < 7500 K
	8.10	tropopause H_2O	NO	
	11.00	HNO_3	O_3, Ocs	
	15.70	N_2O	Clo, HO_2	
	18.05	CO	O,(V = 1)	
	?0.90	pressure/temperature		
64?.85	5.60	CH_3Cl		T_{sys} < 10,000 K
	6.60	ClO	HO_2	
	7.60	BrO	HO_2	
	17.00	tICl	O_3	
	18.00	tIOCl	$tI^{37}Cl$	
	20.51	SO_2		
1228.95	1,50	HF		T_{sys} < 15,000 K
2522.78 (2 channels)	8.47	OH		T_{sys} <30,000 K
	12.83	OH		

IF: 6 broadband HEMT amplifiers (MMIC proposed, discrete narrow-band if necessary)
LO: InP GUNN osc. & planar diode var. mult. to 1230 GHz; CO_2 pumped methanol laser at 2522 GHz
Back End: 17 Acousto-Optic Spectrometers, 1 GHz wide, 1 MHz resolution
Integration time: 0.6 sec   Field of View: 1.5 km at limb (3 km for 216 GHz)

Table II. Room Temperature Waveguide Schottky Diode Mixer Performance ≈ 200 GHz

Approx. Signal Frequency	Whisker Contacted Diode: Single Diode Fund. Mixer		Single Diode Harm. Mixer		Two Diode Subharmonic Mixer			Planar Diode: Two Diode Subharmonic Mixer		
F_{GHz}	T_m	L_{dB}	T_m	L_{dB}	T_m	L_{dB}	P_{LO}	T_m	L_{dB}	P_{LO}
180	750[1]	5.7	2600[5]	10.0	2400[6]	10.5	6.5	2750[8] $T_{Receiver}$		10
205	1250[2]	7.1	2400[5]	9.0	1800[7]	9.6	10	1590[9]	8.7	5.7
								1715[9]	8.7	4.0
								1990[9]	9.3	3.0
230	800[3]	6.2			2400[7]	10.9	10			
	800[4]	6.6								

All results room temperature and for an IF frequency between 1 and 2 GHz unless otherwise indicated.
T_m = single sideband mixer noise temperature in K L_{dB} = SSB conversion loss in dB P_{LO} = required LO power in mW
Blanks: No data found for planar diode fundamental and harmonic mixers at these frequencies in the literature.

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Table III. Diodes Used for the Measurement Results Shown in Table IV.

Description Package Size lxwxt (μm)	Designation Fab. Center	C0 fF	ϕ_b V	η	R_s Ω	I_{Sat}	Anode Diam.	Finger length
GaAs-S.I. substrate 200X80X50	SC1T4/A4 UVa	3.0 3.0	1.09 1.07	1.28 1,25	11.9 1?.6	3X1 0“’” 1×10^{-16}	1.4μm	20 μm
GaAs-S.I. substrate 1 90X75X50	KD138 JPL/UVa	3.5 3.5	1.07 1.07	1.39 1.32	5.0 6.1	6X1 0“’5 2X10”’5	1.4	20
GaAs-thinned, on quartz 240x130x100	SR2T1/H4 UVa	3.0 3.0	1.08 1.06	1.26 1.??	‘6.8 7,7	2X10”’6 1×10^{-16}	1.?	50
GaAs-thinned, no substrate ?40x130x5	SR2T1/G5 UVa	3.0 3.0	1.09 1.07	1.25 1.??	8.1 7,3	2X10”’6 1X10”’6	1.2	50
InGaAs 53%-InP substrate 325x1 25X100	FLI2/A5 UVa	3.0 3.0	.36 ,37	1.26 1,?3	10.6 11.5	1X1 O”’ 6X10”7	1,2	40
InGaAs 53%-thinned, on quartz 300X1 00x50	FLI1/A1 UVa	3.0 3.0	.37 .35	1.29 1.20	6.1 8.1	1X1 O”’ 7X10-7	1.2	40
InGaAs 53%-thinned, no substrate 325x125x5	FLI2/A4 UVa	3.0 3.0	.37 .34	1.30 1.?0	9.4 13,?	1X10”6 1×10^{-6}	1.2	40
Planar Doped Barrier-on quartz 1 85X1 70X70	UMPDB-3 U of Mich.	5.3 5.3	.55 .55	?.? 2.2	?0.0 ?0.0	2X1 0“’	2.0	?0
MMIC diode pair-S.I. substrate 350x120X100	MM2-I3/B4 Martin Mar,	6.0 6.0	.87 .89	“’1.19” 1.?5	10,? lo.?	3X10”’4 4X10”’4	2.0	12
MMIC mixer-S.I. substrate 3265x1280x1 00	MM2B/A6 Martin Mar.	6.0 6.0	.90 .90	1.38 1.38	10.3 10.3	3X1 0-’3 3X1 0-’3	2.0	12

Table IV. Performance of Planar Antiparallel-Pair Diodes in JPL St IP Mixers at ≈ 200 GHz

Diode Type-Substrate	Mixer-Diode Designation	Freq. (GHz)	T_{mixer} (SSB)	Loss (SSB)	Output Imped.	LO Power
GaAs-S.I. substrate	200 A?-SC1T4	?oi	1,600 K	8.7 dB	130 Ω	5.7 mW
GaAs-S.I. substrate	200 B4-KD138	?05	--2,400	10.0	90	4.7
GaAs-thinned, on quartz	?OOB4-SR211	210	1,700	8.7	125	4.0
GaAs-thinned, no Substrate	200 B4-SR?T1	?10	?,000	9.3	125	3,0
InGaAs 53%-InP substrate	200B3-FLI?	?00	5,800	14.1	80	1.4
InGaAs 53%-thinned, on quartz	200A? -FLI1	?10	3,750	12.0	90	1.0
InGaAs 53%-thinned, no substrate	200 B3-FLI?	200	3,800	12.2	90	1.4
Planar Doped Barrier-on quartz	200A? -PDB3	?1O	7,150	13.2	120	1.2
MMIC diode pair-S.I. substrate	200A?-MM2	?00	--4,150	12.5	85	8.0
MMIC mixer (biased)-S.I. substrate	MM3-MM2B	?05	5,?00	13.4	85	3.0

Notes: 1. Diode capacitance values are calculated values based on nominal anode area & depletion width.
2. Diode electrical properties are calculated from measured IV curves. Parameters for both diodes are given.
3. SSB noise and loss are extrapolated from DSB measurements assuming equal sideband response.
4. Physical differences between mixer blocks & diode mounting position result in best performance occurring at slightly different frequencies in each reported case.

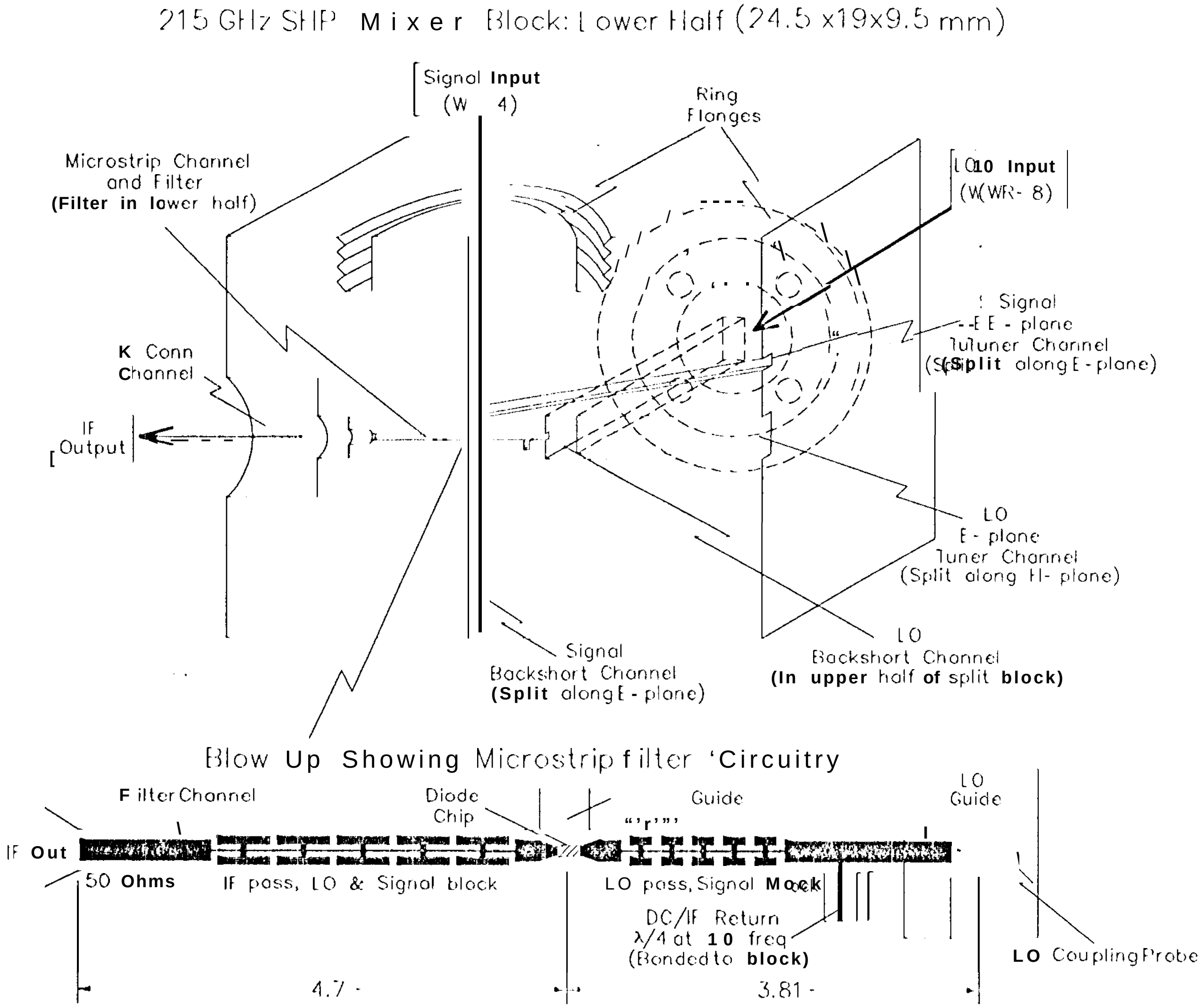

Fig. 1. Schematic of the 2.15 GHz subharmonically pumped crossed waveguide mixer block and microstrip filter circuitry. Only the lower half of the split block is shown. Dimensions arc mm.

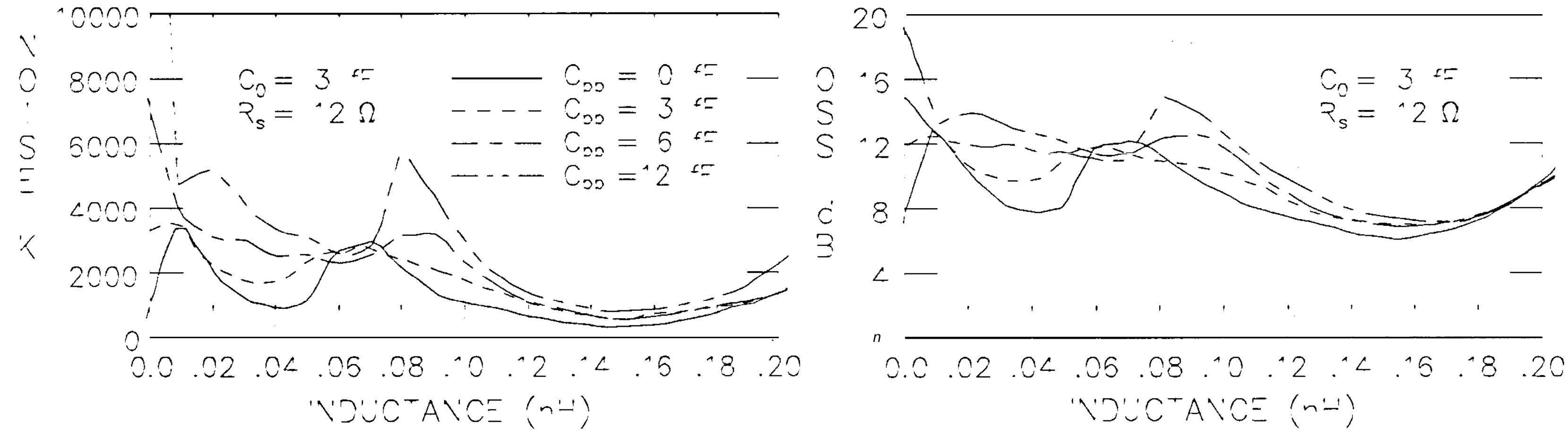

Fig. 2. Computed subharmonically pumped single sideband mixer noise ant' loss versus series (anode finger) inductance and parallel (mid-to-pad) capacitance. The LO and IF frequencies are 215 GHz and 1.5 GHz respectively. The mount impedances at the LO, upper and lower sideband were set to 70 - j12 Ω. The second harmonic sideband impedances were set to 65 + j80 Ω. All higher harmonics were short circuited by the embedding network. Diode parameters for the computation are similar to those listed for the SC1T4 diode in Table III.: $\eta=1.25$, $I_s=2.5\times10^{-16}$, $\phi=1.10$, $C_{j0}=3fF$ and $R_s=12\Omega$. The LO power was adjusted to maintain a diode DC current of 1 mA and varied from 3.5 to 4.5 mW for the data shown.

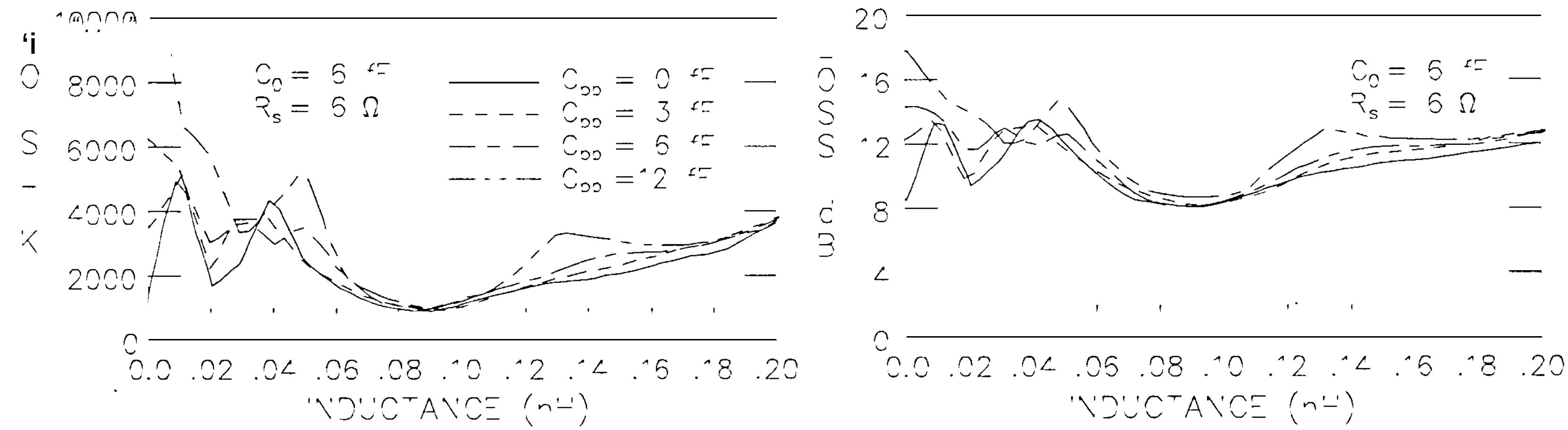

Fig. 3. Computed subharmonically pumped mixer performance *versus series* inductance and parallel capacitance under the same conditions as given in *Fig.* 2 but with $C_{j0}=6fF$ and $R_s=6\Omega$.

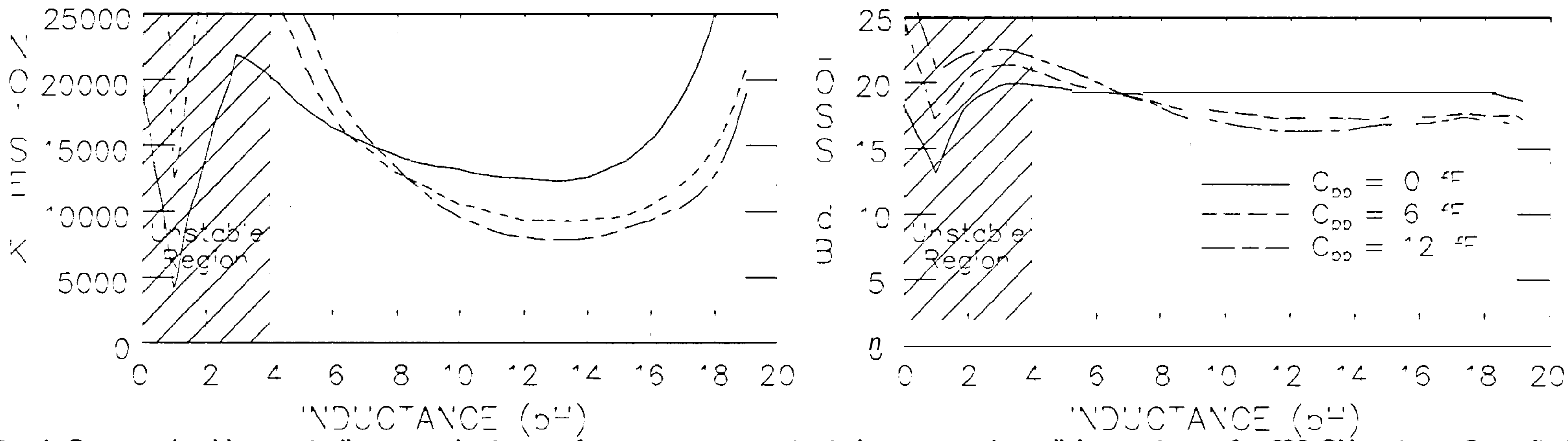

Fig. 4. Computed subharmonically pumped mixer performance versus series inductance and parallel capacitance for 630 GHz using a 2μm diode. Diode parameters for the computation are: η=1.24, I_s=5x10^{-16}, ϕ=1.10, C_o=12fF and R_s=7Ω. The input impedance was set to 16 + j30 Ω at the first harmonic, 64 + j 79 Ω at the second harmonic and short circuited at the higher harmonic frequencies. The LO power was adjusted to maintain a diode DC current of 1 mA and varied from 11 to 20 mW for the data shown.

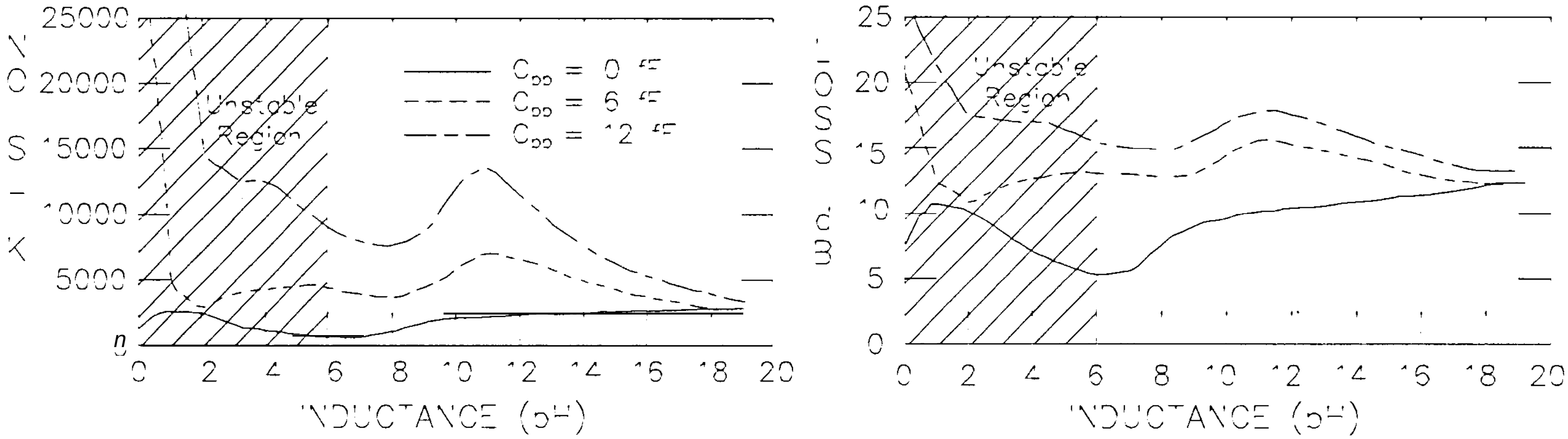

Fig. 5. Computed subharmonically pumped mixer performance versus series inductance and parallel capacitance for a 630 GHz mixer with a 1 μm diode. Diode parameters are taken from a typical KD 138 device and are: η = 1.31, I_s=5x10^{-16}, ϕ=1.10, C_o=3 fF and R_s=12 Ω. The LO power required varied from 5-11 mW for the data presented.